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Magnetic Random Access Memory (MRAM) Device Development

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Abstract

The recent discovery of materials that have anomalous magneto-resistive properties has generated renewed commercial interest in metal-based fast memory storage as an alternative to the currently used semiconductor-based devices. One particularly promising ternary alloy, fabricated at LLNL, appeared to have exceptional field response. This proposal extended the investigation of this class of materials by examining the scaling properties of test structures made from this material that could definitively verify the preliminary observations of high field sensitivity. Although the expected scaling was observed, technical issues, such as excessive oxidation, prevented a definitive assessment of the effect. Despite the difficulties encountered, several test structures demonstrated superior performance in a "spin-valve" configuration that might have applications for very high density recording heads.

Background

One of the most important components present in a computer system is the so-called Random Access Memory (RAM). The bit density and access time of this memory determines in large part the overall performance of the entire system as most users of personal computers know from direct experience. Almost all personal computers and workstations currently use Dynamic RAM (DRAM) technology because of its very favorable cost to performance ratio. This type of fast memory depends upon semiconductor-based, essentially doped-Silicon, materials, hence is relatively inexpensive to manufacture. As memory size increases, however, the necessary reduction in storage bit size will encounter significant technological obstacles that might preclude further development. The primary obstacle to further bit size reduction is widely recognized to be the dielectric material used in the device. This material holds the charge in check so that the device operates correctly when activated by an applied current. In technical terms, the device's capacitance must rise significantly, otherwise each individual bit will no longer operate reliably.

The use of magnetic materials in place of semiconductor materials for RAM has become feasible with the advent of a new class of magnetoresistive materials – the so-called Giant MagnetoResistive (GMR) multilayer stacks. These materials were initially investigated for use in magnetic sensors and have successfully replaced the older generation of inductive read heads to achieve 5- to 10-fold magnetic disk storage densities. The introduction of this technology for RAM development would have several natural advantages: non-volatility, intrinsic radiation hardness, manufacturing compatibility with existing integrated circuit technology, simpler processing steps than conventional DRAM fabrication, and higher bit densities than projected DRAM devices. The outstanding technical obstacle confronting MRAM development is the relatively slow access time. Introducing GMR materials with higher sensitivity can significantly reduce this access time.

The critical issue of increased field sensitivity was directly confronted in this half-year investigation. The specific program of research and development concentrated upon the optical patterning of an optimized, high GMR-response, ternary alloy previously developed by LLNL personnel. This alloy had been investigated originally for use in magnetic read-head applications where its high thermal stability – its retention of high GMR-response during heat treatment – made it an attractive candidate for manufacturing processes. During the course of this research it was discovered that an anomalous field response occurred during patterning. That is, when a sheet of this material was patterned by electron-beam lithography into small, submicron-sized cylindrical dots the magneto-resistance jumped tenfold or more, especially at the smallest feature sizes.

In order to verify the reality of this phenomenon, it was necessary to repeat this scaling behavior under more controlled conditions. Thus, the funded research focussed upon a careful set of scaling experiments in which cylindrical dots of varying radius were fabricated using optical patterning. Although optical lithography cannot produce features as small as electron-beam patterned ones, the ready availability of a high-performance optical stepper at LLNL had sufficient dynamic range to test the scaling behavior at larger feature sizes. In summary,, the critical verification experiments would confirm or refute the earlier partial observation of enhanced response at small feature sizes. If this trend were observed, then another set of experiments would be devoted to the elucidation of the underlying mechanism controlling this unusual behavior.

Sample Fabrication

The scaling experiments included features ranging from two micron radius to 0.35 micron radius. The three important process development steps involved ion beam etching, an image reversal process, and the development of a successful lift-off procedure. These last two steps Each of these steps is discussed briefly below.

Since the magnetic materials used in the multilayer stacks are restricted to the 3d transition metals, it is well known that these particular metals do not readily form volatile by-products in plasma reactions with any known chemically reacting gases. There is typically a large amount of re-deposited material near the structures being fabricated that will seriously compromise the field response of these structures. Thus it is essential to develop an etch process to remove this undesirable material. This step was successfully accomplished using a specially developed technique that selectively removed the magnetic materials using a photoresist layer as a mask in an Argon ion sputtering etch process.

The second technical fabrication challenge arose in the structure definition. The magnetic multilayers that were to be etched were very thin, usually less than 200 Angstroms thick. The electrical contacts to this thin stack consists of a thick metal layer that is several thousands of Angstroms thick. The process developed in this project involved sputtering the electrical lead material over the patterned GMR stack, followed by photolithographic definition of the lead structure. Ion beam etching is then used to remove the undesirable re-deposited material. The crucial point is to avoid over-etching of this material since the underlying, thin, GMR stack will be partially or totally removed during this step. To facilitate this overall procedure, an image reversal process, rather than a lift-off process, was used. The image reversal process requires several extra process steps but it had an important advantage since an additional mask was not required for the subsequent life-off process.

The final fabrication step involved a lift-off procedure applied to the image-reversed structure defined in the second step. The image reversal converted the pattern so that the electrical lead material could be deposited on the GMR contact area as well as on the resist where the lead material is superfluous. Dissolving the resist underlayer coating in acetone then removes this extraneous material from the wafer. This process had the singular advantage of avoiding an etch step to remove the electrical lead material and thus preserving the thin GMR stack buried beneath the leads. This lift-off step required a highly directional metal evaporation so that metal does not coat the resist sidewall which would prevent the acetone from dissolving the underlying resist.

Images of the structures produced after this sequence of process steps are shown in Figures 1, 2 and 3 that have photoresist remaining. In these figures, the electrical contact strips overlap the GMR multilayer stacks. Two different GMR stacks are displayed in Figures 1 and 2: 1.90 micron and 0.4 micron width. An expanded scale view is provided of the smaller structure in Figure 3. Although these structures are well-defined at this point in the processing, a final planarization step is necessary to complete the sample preparation. This remaining step unfortunately presented a severe difficulty for the smallest features. Overly aggressive chemical-mechanical planarization appeared to remove the smallest structures entirely from the wafer and this difficulty could not be overcome in the few months devoted to this project.

Results

The largest fabricated features did indeed display a similar scaling response as that observed earlier but the failure of the small, less than 0.5 micron width devices, prevented the completion of a definitive experiment. The magneto-resistive response was easily tracked for the larger structures and a large amount of information was gathered for these structures using a probe station. Oxidation of the samples was also an important limitation since direct contact with the electrical leads was difficult or impossible for some structures. The outstanding difficulty remains the planarization step. Alleviating this problem requires more development before it can be applied to these thin, small devices.

Conclusion

It appears from the above experiments that the previous observations of enhanced response were correct and that partial oxidation of the patterned features is the primary cause. A successful process development sequence was developed that might be useful in the future for further investigation of spin-valve read-head structures or MRAM test structures. Further process development is still required to demonstrate that this effect can be usefully controlled to permit technological applications.

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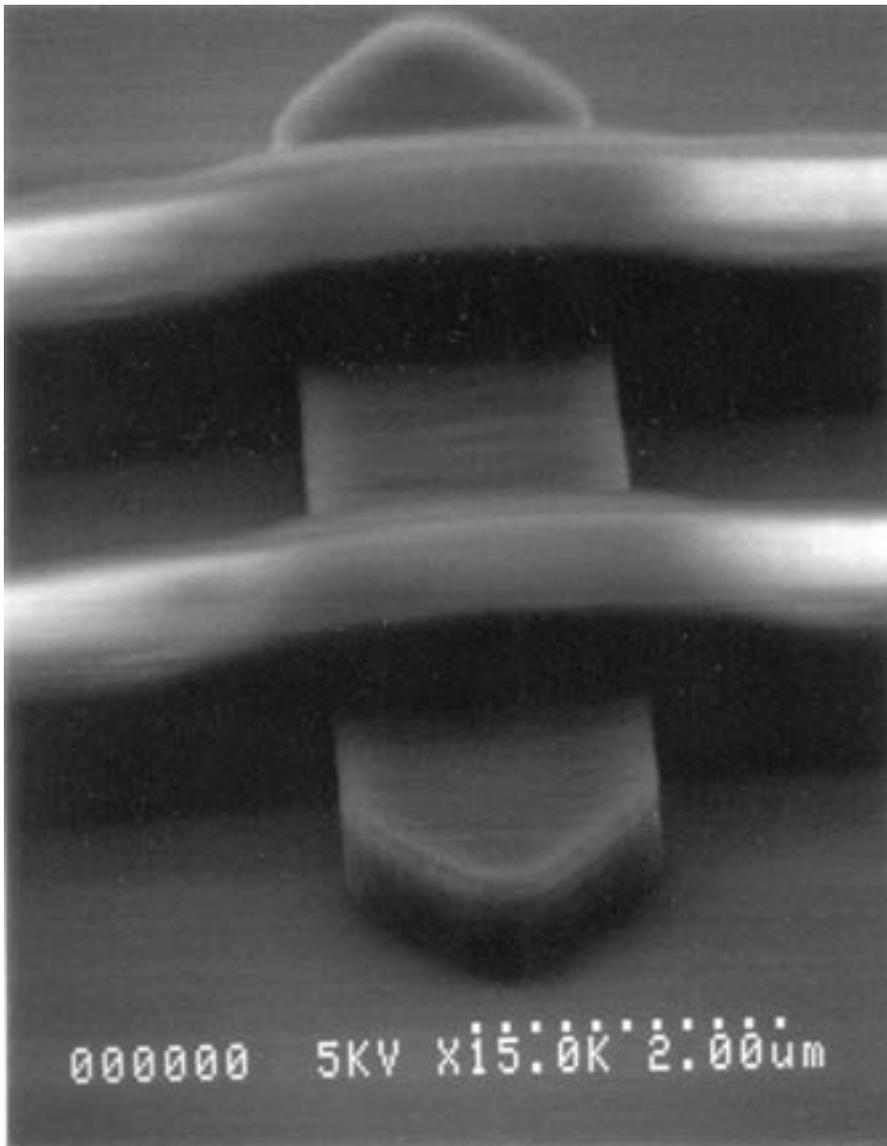


Figure 1

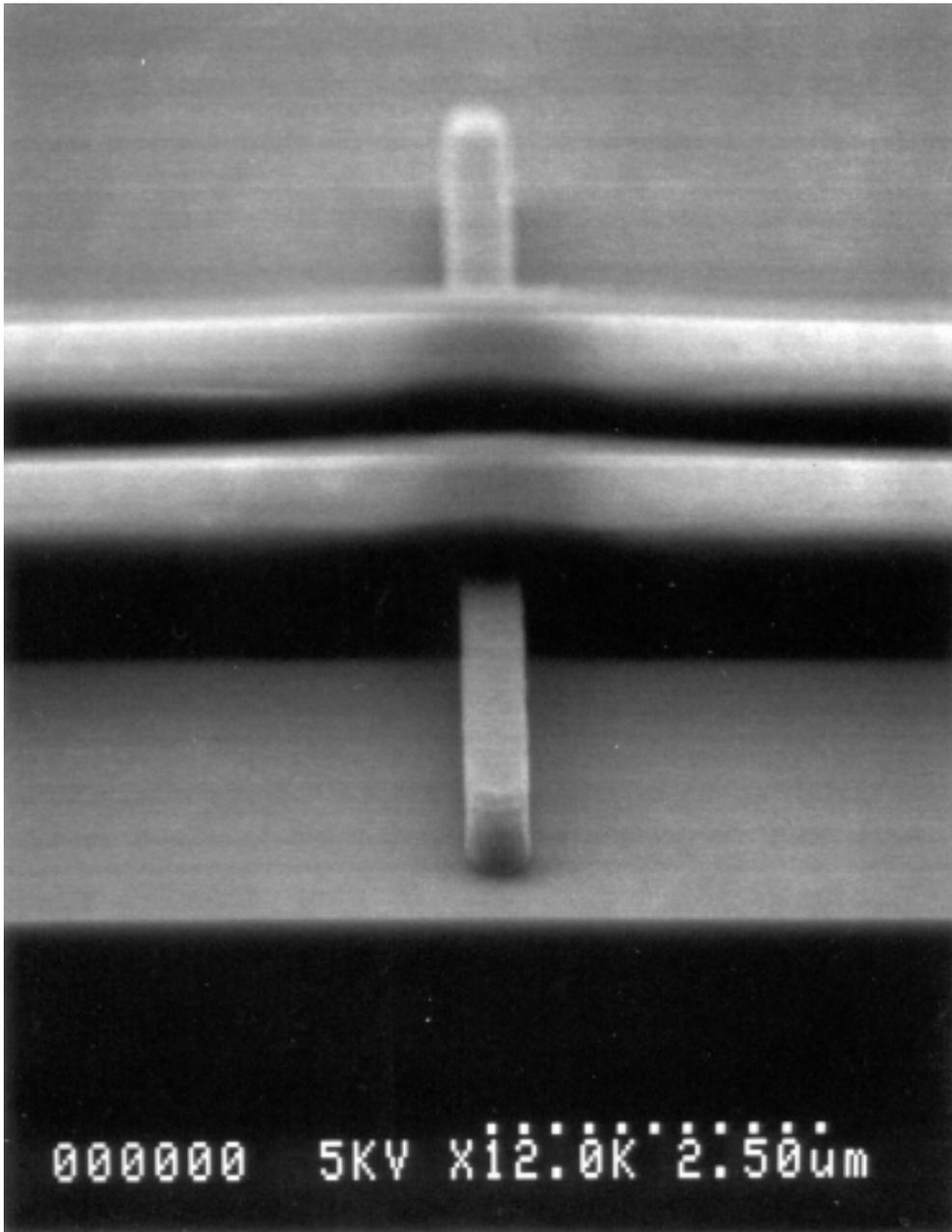


Figure 2

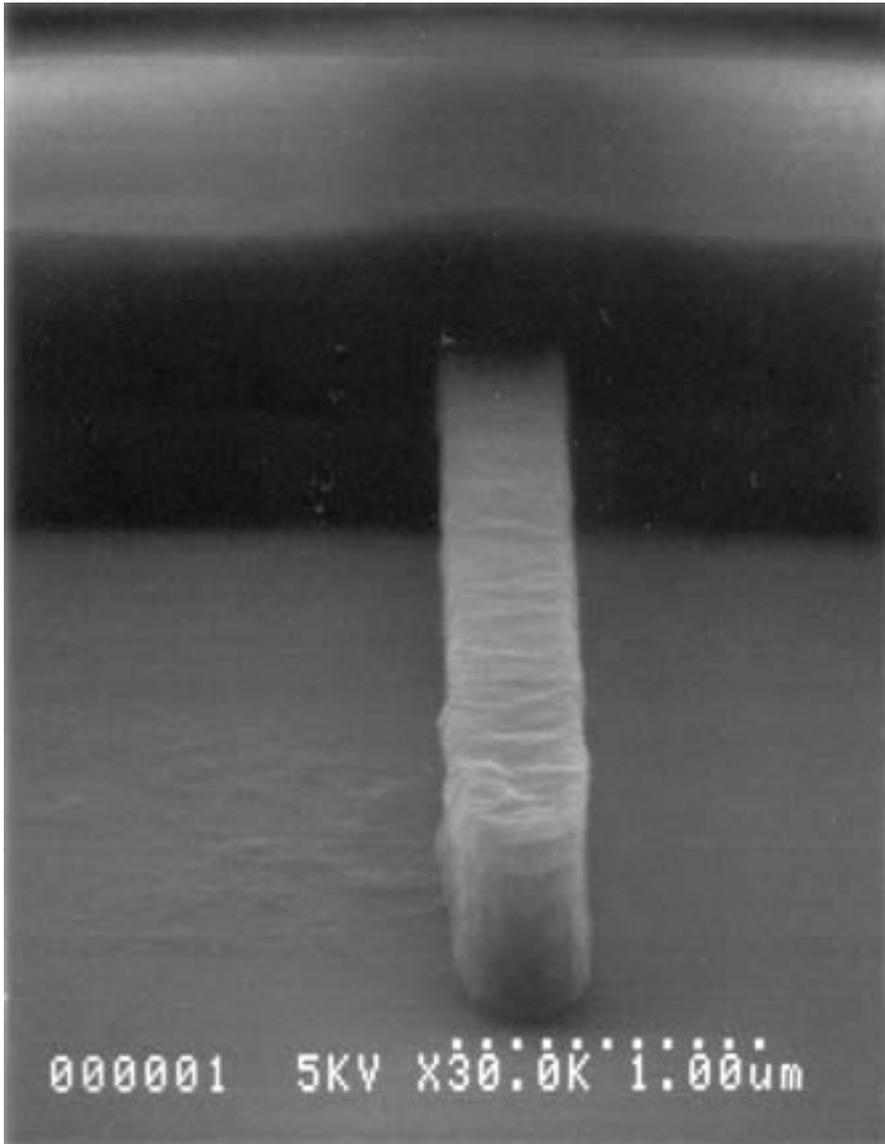


Figure 3